

Drag Characterization of Strut-mounted 'Through Cavity' for Scramjet Applications

Tahzeeb Hassan Danish¹, Sathiyamoorthy K², Srinivas J³, Manjunath P⁴

¹) Scientist, Propulsion Division, National Aerospace Laboratories
thdanish@nal.res.in

²) Senior Scientist, Propulsion Division, National Aerospace Laboratories
sathy_cim@nal.res.in

³) Technical Officer, Propulsion Division, National Aerospace Laboratories
seemu-nal@nal.res.in

⁴) Senior Principal Scientist, Propulsion Division, National Aerospace Laboratories
manjunathp@nal.res.in

Abstract

Wall mounted cavity has proven to be a capable candidate for fuel air mixing and flame stabilization for scramjet. Because of inherent advantages like symmetric flow, avoidance of base wall cooling, symmetric fuelling feasibility etc exploration of strut-mounted 'through cavity' has been done. It is a novel configuration formed in the space between two struts immersed in a supersonic flow in tandem. Two variants of the cavity, formed by using rectangular and ramp strut as the rear strut and plug nozzle acting as the forward strut, have been used. Drag characterization is carried out by static pressure measurement inside the cavity for different aspect ratios for these two types of cavities formed. Flow visualization has been done using time averaged Z-type schlieren technique. Open and closed cavities have been identified using distribution of coefficient of pressure in the cavity and the schlieren images taken.

Keywords: Scramjet, Strut-mounted through cavity

1. Introduction

Scramjet engines are the most promising candidates for future air breathing propulsion system. Air flow at supersonic speed in scramjet combustor results in very low residence time of the order of 1 millisecond. So the available time for fuel-air mixing, atomization, vaporization and combustion is very low. Hydrocarbons used as fuel for their high energy content and ease to handle have certain amount of vaporization and ignition delay. So flame holding becomes a difficult task. One candidate for such a case of harsh environment is the properly designed cavity in the flow field. Figure 1 shows a typical wall mounted cavity, where L , D and θ are length, depth and ramp angle of the cavity respectively. Ratio of length to depth of the cavity is called as aspect ratio of the cavity.

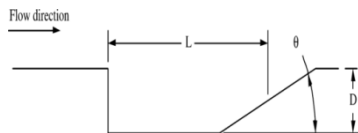


Figure 1. A typical wall mounted cavity

Flow field in the scramjet cavity flame holder is described by following features as depicted in Figure 2.

- Oblique shock wave series at the front edge.
- Shear layer starting at the leading edge.
- Impact shock wave at the rear wall.
- Expansion wave or bow shock at the rear edge.[1]

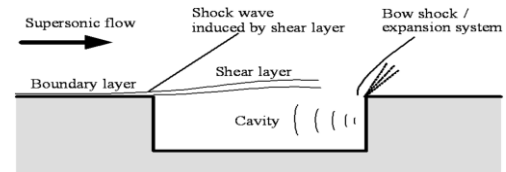


Figure 2. Flow field in a cavity, [2]

If shear layer spans from leading edge to all length of a cavity then it is called as open cavity. But when the cavity is long enough that shear layer attaches to the bottom wall of cavity, then it is called as a closed cavity. Open and closed wall-mounted cavities can be seen in figures 3 and 4.

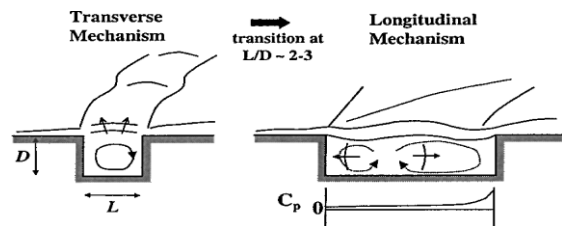


Figure 3. Wall mounted open cavities, [3]

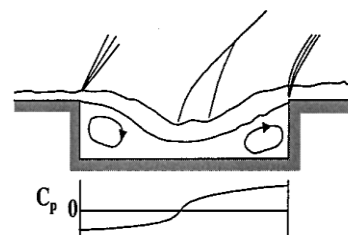


Figure 4. Wall mounted closed cavities, [3]

Critical value of L/D is approximately 7 for wall-mounted cavities. Critical value of L/D at which transition between cavity flow regimes occurs also depends on boundary layer thickness at the leading edge of the cavity, the flow Mach number and the cavity width. Closed cavity gives higher entrainment than open cavity. The pressure increase in the back wall vicinity and the pressure decrease in front wall results in higher drag in the closed cavity than the open cavity. As the cavity changes from open to closed, it results in steep rise in Coefficient of pressure along the length of the cavity as we go from forward end to the rear end of the cavity. [3]

Residence time, T , of the flow inside cavity is a direct function of mass exchange rate. In the open cavity, mass and momentum transfer mechanism is controlled by longitudinal oscillation and vortex structure inside the cavity. Computational visualization of Gruber et al. [4] demonstrated the existence of one large vortex stationed near the trailing edge of the cavity and a secondary vortex near the upstream wall. The mass exchange of the cavity is controlled by the large trailing vortex, which interacts with unstable shear layer. The mass exchange between the vortices inside the cavity, on the other hand is relatively small. Therefore as the trailing edge vortex occupies larger volume inside the cavity, the mass exchange increases and T decreases. Consequently the steady state numerical calculation showed the T for large cavity ($L/D=5$) is smaller than small cavity ($L/D=3$). Hence as the aspect ratio is increased, the cavity residence time is decreased.

Because of inherent advantages like symmetric flow, avoidance of base wall cooling, symmetric fuelling feasibility etc exploration of strut-mounted 'through cavity' has been done. It is a novel configuration formed in the space between two struts immersed in a supersonic flow in tandem. A typical strut-mounted through cavity is shown in Figure 5:

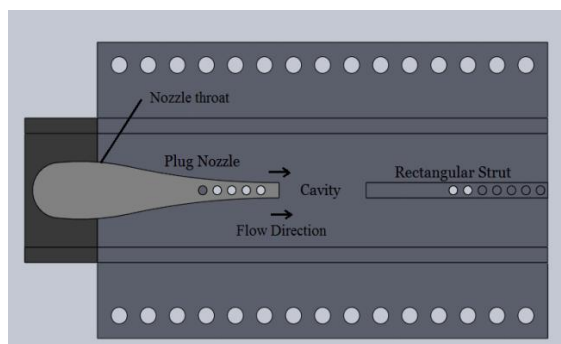


Figure 5. Test section showing strut-mounted through cavity

2. Experimental Details

2.1 Experimental Set-up

Tests were conducted at High Speed Combustor Test Facility, Propulsion Division, NAL, Bangalore. The air total pressure was controlled using a gate valve and a butterfly valve. A transition duct was connected to the rig (150 mm diameter) which changed the flow to 2-D rectangular (68 x 50 mm²). It was connected to the test section which contained the Plug Contour Nozzle designed to give Mach number 2 and a rear strut. The nozzle and the strut formed a strut mounted through cavity. The cross section of the test section was 75 x 50 mm². Figure 6 gives a view of experimental set up.



Figure 6. A view of experimental set up

The thickness of the rear strut was 10 mm. Two types of rear struts were used to make two configurations of cavity:

- Rectangular strut having dimension of 125 x 50 x 10 mm³ (Rectangular Cavity)
- Rectangular strut of same dimension as a), but with aft ramp angle of 60° (Ramp Cavity)

Mach number at leading edge of the cavity was 2.03 ± 0.02 , total pressure was 7 ± 0.1 bar and total temperature at the entrance of test section was 300 K. Depth of the cavity is equal to half the thickness of the rectangular strut i.e. 5 mm and width of the cavity was 50 mm. Length of the cavity and hence L/D ratio (aspect ratio of the cavity) was changed by changing the position of the rear strut. Length of the cavity was varied in the steps of 10 mm from 20 mm to 70 mm. Thus it gave aspect ratios of 4, 6, 8, 10, 12 and 14.

2.2 Measurement Plan and Data Acquisition

Static pressure measurements at the end of the transition duct and the end of plug nozzle gave the total pressure and the Mach number seen by the cavity. As the nozzle is a contour nozzle, it gives a very clean flow. Static pressure measurements were taken at one side of the cavity. Pressure ports of 1 mm diameter were made on the side plate such that they were at the mid plane of the cavity. The static ports were at pitch of 5 mm with the first port at 2.5 mm from the end of the plug nozzle. Measurement plan can be seen in Figure 7.

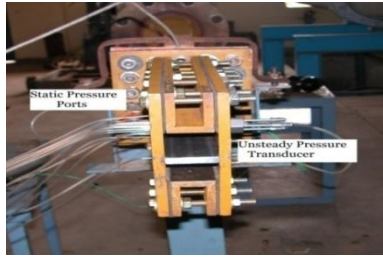


Figure 7. Test section with static pressure ports and unsteady pressure transducer

For static pressure measurements, thin film piezo-resistive type pressure transducers, PCB 1503B02 in 17 numbers were used. They have measurement range of 0 to 115 psi, output from 4 to 20 mA, accuracy <0.25% of FS, resolution < 0.01% of FS, sensitivity of 0.139 mA/psi and response time < 1 ms.

2.3 Schlieren Set-up

For capturing the flow structure a time averaged Z-type Schlieren technique with horizontal knife edge was used. An incandescent lamp was used as the light source. Nikon D7000 was used with a lens of focal length 210 mm.

3. Results and Discussion

3.1 Drag Characterization

The general trend of the pressure inside the cavity is that it first decreases and then rises to a certain value. In most of the cases the pressure coefficient is positive i.e. the pressure inside the cavity is more than the freestream condition at the entrance of the cavity except for the cases of aspect ratios of 12 and 14. Coefficient of pressure is calculated assuming the nozzle exit as the freestream and plotted against non-dimensionalized length of the cavity x/L , where x is the position of pressure port from the exit of the nozzle and L is the length of cavity. For high aspect ratios of 12 and 14 C_p was found negative very close to the forward end of the cavity, but these negative values of C_p were very low in magnitude.

As the aspect ratio is increased the magnitude of coefficient of pressure increases along the axial length of the cavity. For rectangular strut, C_p values rise up to 0.09 for low aspect ratios but at higher aspect ratio of the cavity the pressure builds up more and the C_p reaches as high as 0.5. Steep rise in C_p near the trailing edge of cavity starts at aspect ratio of 12. So the cavity becomes closed for aspect ratio 12 and above. Aspect ratio of 10 appears to be the transition from open to closed cavity. Distribution of coefficient pressure along the length for rectangular cavities is presented in figures 8 and 9.

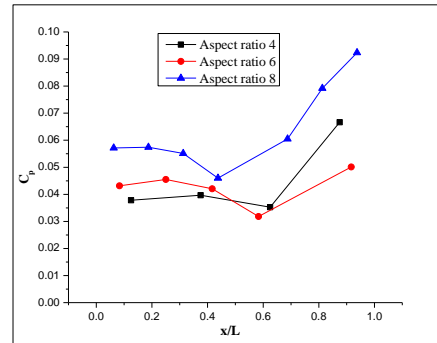


Figure 8. C_p distribution for low aspect ratios in rectangular cavity

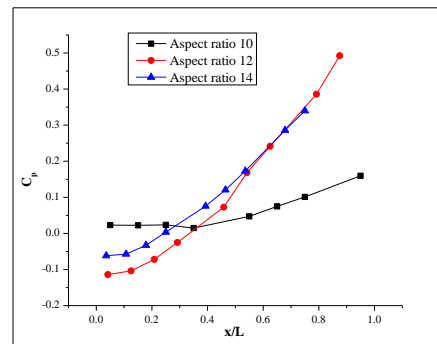


Figure 9. C_p distribution for high aspect ratios in rectangular cavity

A similar trend is observed in the case of ramp cavity, but rapid rise in C_p near the trailing edge of the cavity occurs at the aspect ratio of 10 rather than aspect ratio of 12 as in the case of rectangular cavity. Thus it can be observed that aspect ratio 10 and above are closed cavity region and aspect ratio of 8 is the transition point from open to closed cavity in this type of cavity. Providing ramp angle at the rear strut causes the cavity to be closed at lower aspect ratio. Variation of coefficient of pressure along the length of the cavity is depicted in figures 10 and 11.

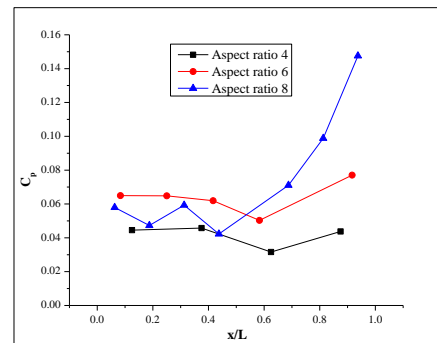


Figure 10. C_p distribution for low aspect ratios in ramp cavity

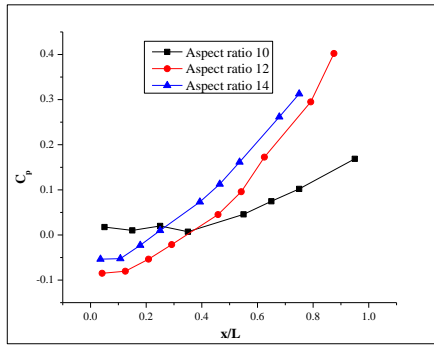


Figure 11. C_p distribution for high aspect ratios in ramp cavity

As shown in figure 12, at lower aspect ratio of 6, ramp cavity gives higher C_p values than the rectangular cavity. Hence it gives higher entrainment but possess higher drag also. For the aspect ratio of 8, both of the rectangular and the ramp cavities show almost same C_p distribution, except very near to the trailing edge of the cavity, where the ramp cavity shows higher C_p values than the rectangular cavity. This can be seen in figure 13.

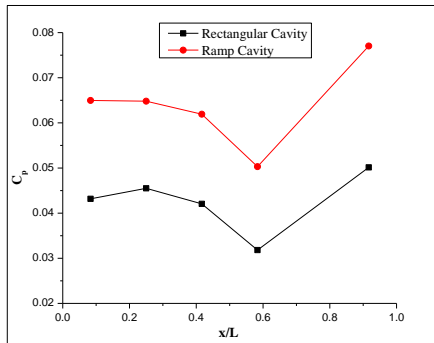


Figure 12. C_p distribution for aspect ratio 6

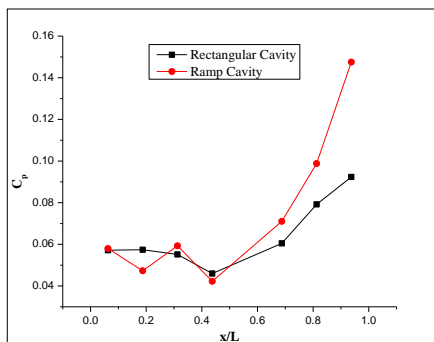


Figure 13. C_p distribution for aspect ratio 8

For higher aspect ratio, both of the rectangular and ramp cavities give almost same pressure distribution. C_p distribution for aspect ratio of 10 for both of the rectangular and ramp cavities is depicted in figure

14. The reason for almost same values of coefficient of pressure is that the cavity is becoming closed.

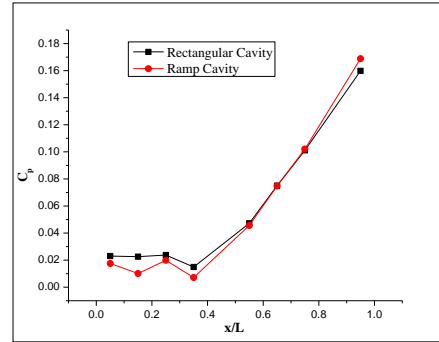


Figure 14. C_p distribution for aspect ratio 10

3.2 Flow Visualization by Schlieren Technique

A Z-type time averaged Schlieren technique with horizontal knife edge was adopted to visualize the flow structure of strut-mounted through cavity. Figure 15 shows, a rectangular cavity having aspect ratio of 4. The shear layer spans through the full length of the cavity and attaches to the rear strut. An oblique shock at the leading edge and a bow shock at the trailing edge of the cavity can be seen in this figure. It is an open type of cavity. Figure 16 shows a rectangular cavity with aspect ratio of 12. Here the cavity is long enough, such that the shear layer is not attaching to the rear strut, but it is interacting with the shear layer coming from the symmetrical side. Here instead of oblique shock we get an expansion fan. Bow shock is also replaced by expansion fan. A re-attachment shock can also be seen.

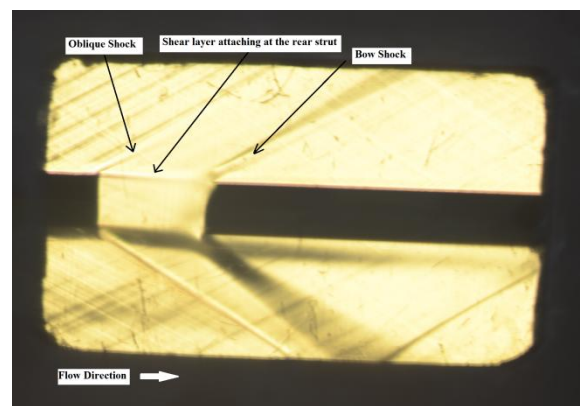


Figure 15. Schlieren image for rectangular cavity at aspect ratio 4

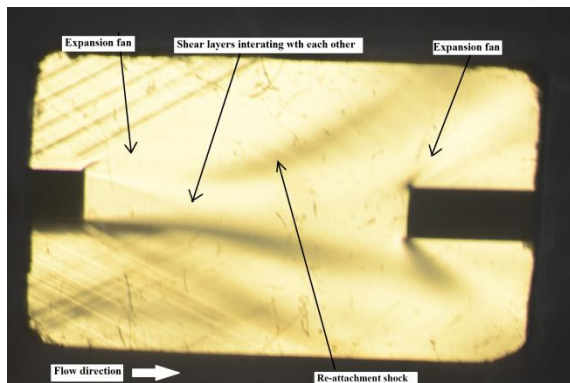


Figure 16. Schlieren image for rectangular cavity at aspect ratio 12

4. Conclusions

As the aspect ratio is increased the magnitude of coefficient of pressure increases along the axial length of the cavity. For rectangular cavity, aspect ratio of 10 appears to be the transition from open to closed cavity. Ramp cavity causes the cavity to become closed earlier and aspect ratio of 8 appears to be the transition from open to closed cavity. Schlieren images show the flow structure as expected and effects of change of aspect ratio from open to closed are also observed.

5. Acknowledgement

The authors wish to express their sincere thanks to the Director and the Head, Propulsion Division, NAL for providing all the necessary support. The authors would like to thank Mr. Pratheesh Kumar P, Mr. Venu G, Mr. Jayprakash C and Mr. M Satish Kumar for their contributions in the experimental work.

6. References

- [1] Tianwen Fang, Meng Ding and Jin Zhou, "Supersonic Flow Over Cavities", Translated from Journal of National University of Defence Technology, (2007).
- [2] Youngki Lee, Minsung Kang, Heuydong Kim and Toshiaki Setoguchi, "Passive Control Techniques to Alleviate Supersonic Cavity Oscillation", Journal of Propulsion and Power, **24** (4) (2008).
- [3] Adela Ben-Yakar and Ronald K Hanson, "Cavity Flameholder for Ignition and Flame Stabilization in Scramjets: An Overview", Journal of Propulsion and Power, **17** (4) (2001).
- [4] J. Gruber, M. R., Baurle, R. A., Mathur, T., and Hsu, K. Y., "Fundamental Studies of Cavity-Based Flame-Holder Concepts for Supersonic Combustors," 35th AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit, Los Angeles, California, (1999), P-99-2248.